Performance analysis of two new code families for spectral-amplitude-coding optical CDMA systems

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Performance Analysis of Two New code families for Spectral-Amplitude-Coding Optical CDMA Systems

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Abstract—**In this paper, we have proposed two new 1-D code families for spectral amplitude coding optical code-division multiple-access (SAC-OCDMA) systems. They are referred to as (i) partitioned diagonal code (PDC) and (ii) partitioned modified quadratic congruence code (PMQCC). Simulation results show that both of codes can reduce phase-induced intensity noise (PIIN) and support more active users as compared with MQC. Our results show that for similar code length PDC and PMQCC can support 11% and 14%, respectively, more simultaneous users as compared with MQC. Also at each synchronous time, the auto-correlations of PDC and PMQCC reach to their peak values and their cross- correlations remain one.**

Index Terms—**Spectral amplitude coding (SAC), optical code-division multiple-access (OCDMA), phase-induced intensity noise (PIIN), partitioned diagonal code (PDC), partitioned MQC code (PMQCC).**

I. Introduction

OPTICAL code division multiple access (CDMA) systems have been proven to be very helpful in combining the unlimited bandwidth of fibre with flexibility of CDMA technique to achieve high-capacity transmission. Currently, there are different types of OCDMA systems including wavelength-hopping coding OCDMA, spectral phase coding (SPC) OCDMA, time-spreading coding OCDMA and spectral amplitude coding (SAC) OCDMA systems. However, among them, SAC-OCDMA system has been proven to be very promising [1] as by employing an appropriate code families and detection scheme [2]-[3] it can significantly reduce the negative effect caused by the multi-access interference (MAI) and the receiver shot, dark current and thermal noise sources [4].

However, in a SAC-OCDMA system, phase intensity induced noise (PIIN) which originates from the incoherency of the broadband light sources [5] severely affects the system bit error rate (BER). This limits the number of active users that a SAC-OCDMA system can support. In order to reduce the BER and increase the number of active users, PIIN and receiver noise sources must be suppressed. Due to the system implementation of both 2-D and 3-D codes are complex (i.e. need more star couplers, FBGs and additional switches as discussed in [6]-[9]), most researchers are focusing on 1-D code is because of its simplicity of its code structure, implementation and cost effectiveness. A number of 1-D codes have been reported in the literature including the maximal-length sequence (M-sequence) codes [10], Walsh-Hadamard codes [10], balanced incomplete block design (BIBD) codes [11] and zero cross correlation (ZCC) code [12]. In [13], modified double weight (MDW) code with ideal in-phase cross correlation (IPCC) has been proposed which performs better than Hadamard code with easy and efficient code construction. In [14], random diagonal (RD) code with zero cross correlation at data segment has been proposed to reduce the PIIN. Meanwhile, the proposed new spectral direct detection technique in [14] utilizing RD code considerably improves the system performance as compared with the conventional SAC complementary subtraction technique [14]. In addition, two codes referred to as the modified quadratic congruence (MQC) code and the modified frequency hopping (MFH) code were proposed in [15], both of them outperform the Hadamard code, in particular MQC code that supports p^2 cardinalities with code weight and length of $(p+1)$ and (p^2+p), respectively, where p is a prime number. The MQC was widely regarded as a standard code among the other existing 1-D codes in Optical CDMA systems. Although, both MQC and MFH code have improved the SAC-OCDMA system performance (i.e. bit error rate) however, it can be further improved by changing the structure of these codes. As for the system implementation, recently a few experimental research papers are reported [16], which is a great indication that practical implementation of OCDMA networks will happen in near future.

In this paper, we have introduced, for SAC-OCDMA system, two new codes namely (i) partitioned diagonal code (PDC) which is based on modified RD code and (ii) partitioned modified quadratic congruence code (PMQCC). The

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performances of these new codes have been analysed and compared with MQC codes as MQC code is designed to have good periodic auto/cross correlation properties and effective bandwidth use [17]. Meanwhile, to make the results more comparable, a specific prime number is chosen to let MQC code have as close as possible code length with that of PMQCC.

The rest of this paper is organised as follows. In Section II, constructions of both PDC and PMQCC are explained. The new codes evaluation and comparisons are explained in Section III. In Section IV, the performance analysis of SAC-OCDMA system employing PDC and PMQCC as well as comparisons between these two new codes and MQC code are presented. Finally, the conclusion is given in Section V.

II. Construction of Proposed New Codes

A. *Construction of partitioned diagonal code (PDC)*

Due to the nature of signaling limitation, in the SAC-OCDMA system, the code sequence consists of unipolar (0, 1) sequences. In this paper, we denote a code by (N, w, λ) where N is the code length, w is the code weight and λ is the in-phase cross correlation, $\lambda = \sum_{i=1}^{N} x_i y_i$ of two different code sequences $X = (x_1, x_2, \dots, x_N)$ and $Y = (y_1, y_2, \dots, y_N)$. We also define $\lambda = 1$ as the ideal in-phase cross correlation. In this code construction, the code sequences consist of binary number instead of integer number.

Let us first have a quick review of the random diagonal (RD) code. Details regarding the construction of this code can be found in [14]. Random diagonal code is constructed by combining data and code segments together. Let us denote *'K'* as the number of users. We define the data segment $[Y_1]$ as the anti-diagonal matrix $(K \times K)$ which has zero in-phase cross correlation. For example, when $K = 3$, Y_1 can be expressed as:

$$[Y_1] = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

The code segment $[Y_2] = [B \vdots M]$ where it consists of two parts namely the basic matrix [B] and the weight matrix [M] where for $K = 3$ matrices [B], [M] and $[Y_2]$ can be expressed as:

$$[B] = \begin{bmatrix} 0\,1\,1 \\ 1\,1\,0 \\ 1\,0\,1 \end{bmatrix} \quad [M] = \begin{bmatrix} 1\,0 \\ 0\,1 \\ 1\,0 \end{bmatrix} \quad and\ [Y_2] = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 \end{bmatrix}$$

Note that $[Y_2]$ is obtained by combining matrices [B] and [M]. The final step to obtain the RD code sequence, [Z], is to cascade $[Y_1]$ and $[Y_2]$ that is $[Z] = [Y_1 \vdots Y_2]$. The matrix [Z] has N columns and K rows where N is the code length. For example when $K = 3$ and $N = 8$ the RD code [Z] is:

$$[Z] = \left[\begin{array}{ccc||ccccc} 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{array}\right]$$

Partitioned diagonal code (PDC) family is constructed base on the RD code. We remove the code segment matrix of RD code and use several diminishing matrixes instead. Geometric method is used here to construct the PDC. To increase the code weight, another similar data segment was added into the matrix. The partitioned diagonal code is constructed by using the following 11 steps.

Step-1: define an odd integer number S and set up a diagonal matrix $[Y_{S-1}] = (S-1) \times (S-1)$ where in here S is the number of users when partitioned number equals to 1. For example, for $S = 5$ we have:

$$[Y_4] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Step-2: define $[V_{S-1}] = [Y_{S-1} \vdots Y'_{S-2}]$ where $[Y'_{S-2}]$ is the anti-diagonal matrix so for $S = 5$ we have:

$$[V_4] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & \mathbf{1} \\ 0 & 1 & 0 & 0 & 0 & \mathbf{1} & 0 \\ 0 & 0 & 1 & 0 & \mathbf{1} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

As the above matrix shows the positions of all ones form a 'V' shape and also elements of $[V_4]$ are symmetric with respect to the last column of matrix $[Y_4]$.

Step-3: decrease the odd integer number S by 2 $(S = S - 2)$ until $S = 3$ and repeat the steps 1 and 2. For example when $S = 5$ we have:

$$[V_2] = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Step-4: define an upper matrix $[U] = [V_{S-1} \vdots V_{S-3} \vdots \cdots \vdots V_2])$ which for the above example, the matrix [U] is:

$$[U] = \left[\begin{array}{ccccccc|ccc} 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

The matrix $[U]$ clearly shows that the in-phase cross correlation between any two code sequences is zero.

Step-5: As for the same initial value of S, define the diagonal matrix $[\,I_{S-1}]$ which is the same as $[Y_{S-1}]$ that is for $S = 5$ we have:

$$[I_4] = [Y_4] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Step-6: create an anti-diagonal matrix $[I'_{S-2}]$ and then decrease S by two units. For example when $S = 5$ we have:

$$I'_3 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

The new S value would be 3 and we define matrix $[I_{S-2}] = [I'_{S-2}]' = [I''_{S-2}]$ (note $[I] = [I']' = [I'']$).

Step-7: repeat step-6 until the new $S = 1$). Hence, in this example, we have following two matrices:

$$I''_2 = I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \ \&\ I'_1 = [1]$$

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Step-8: cascade the matrices we obtained in steps-5, 6 and 7 sequentially to form the lower line matrix $[L]$ so in case of $S = 5$ we have:

$$[L] = \left[\begin{array}{cccc|ccc|cc|c} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \end{array}\right]$$

Step-9: form the following two new matrices $\begin{bmatrix} U \\ 0 \end{bmatrix}$ and $\begin{bmatrix} 0 \\ L \end{bmatrix}$ where each has S rows (i.e. the same as the number of users without partitioned) and $S(S-1)/2$ column (i.e. which is the same as the code length).

Step-10: the two new matrices define in step-9 have the same number of columns and rows so by completely overlapping matrices $\begin{bmatrix} U \\ 0 \end{bmatrix}$ and $\begin{bmatrix} 0 \\ L \end{bmatrix}$ we can form a new matrix [m]. For $S = 5$ we have:

$$[m] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

It should be noted the code weight of each row in matrix [m] is more than those of matrices [U] and [L]. Also as [m] shows the in-phase cross correlation between any two code sequences is exactly equal to 1 and the code weight of RD code is equal to $(S-1)$.

Step-11: in order to increase the number of active user, partitioned technique is introduced here. Let us define M as a positive partitioned number. The final PDC sequences can be obtained from the following matrix:

$$\begin{bmatrix} [\mathbf{m}] & [\mathbf{0}] & [\mathbf{0}] & [\mathbf{0}] & \cdots & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{m}] & [\mathbf{0}] & [\mathbf{0}] & \cdots & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{0}] & [\mathbf{m}] & [\mathbf{0}] & \cdots & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{0}] & [\mathbf{0}] & [\mathbf{m}] & \cdots & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{0}] & [\mathbf{0}] & [\mathbf{0}] & \ddots & \vdots \\ [\mathbf{0}] & [\mathbf{0}] & [\mathbf{0}] & [\mathbf{0}] & \cdots & [\mathbf{m}] \end{bmatrix} = [\mathbf{F_M}]$$

For $M = 3$ the PDC family $[F_3]$ becomes:

$$[F_3] = \begin{bmatrix} [m] & [0] & [0] \\ [0] & [m] & [0] \\ [0] & [0] & [m] \end{bmatrix}$$

Where [0] represents the zero binary matrix. As the PDC construction shows, both the total number of users and the code length have increased to MS and $MS(S-1)/2$ respectively, after partitioned number is introduced. It should be noted that when the partition number M=1 the in-phase CC is 1 however, when $M \neq 1$, the in-phase CC is either 0 or 1. In this case, we use average in-phase CC which is defined as the ratio of the total collisions between any two codes and the total combinations between any two codes. That is:

$$\bar{\lambda} = M \binom{S}{2} \Big/ \binom{MS}{2}.$$

Finally, the PDC can be denoted as$(MS(S-1)/2,\ (S-1),\ \bar{\lambda})$. Table-I below shows an example of partitioned diagonal code (PDC) when $M = 1$ and $S = 7$ where K is the total number of users (which equals to $M \times S$) and k is the Kth user. The in-phase CC in this example is exactly 1.

TABLE I
PARTITIONED DIAGONAL CODE (PDC) WHERE M=1 AND K=7

K	Code length																				
1	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**1**
2	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**
3	0	1	1	0	0	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	0
4	0	0	1	1	0	0	0	1	0	1	0	1	0	0	1	0	0	0	0	0	0
5	0	0	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	1	0	0	0
6	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	0	1	0	1	0	0
7	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	1	1

B. Construction of Partitioned modified quadratic congruence code (PMQCC)

In the following first we review briefly the construction of the modified quadratic congruence (MQC) code which is based on the quadratic congruence (QC) code that has been proposed in [18]. MQC code can be simply generated by constructing a sequence of integer numbers $y_{d,\alpha,\beta}^{MQC}(t)$ and a sequence of binary numbers $S_{d,\alpha,\beta}^{MQC}(i)$ [15] where $t = 0,1,2,\ldots,p-1$, $d \in \{1,2,3,..,p-1\}$, and $\alpha,\beta \in \{0,1,2,\ldots,p-1\}$. For each fix b and d, the resulted codes can support p^2 cardinalities with weight of $(p+1)$ and length of (p^2+p), where $p > 2$ is a prime number. One important property of MQC code is that the in-phase cross correlation between any two code sequences is equal to 1 which is called ideal in-phase cross correlation. Table-II shows an example of MQC code for the prime number $p = 5$ and $b = d = 1$.

TABLE II
MQC CODE EXAMPLE FOR P=5

α,β	$y(k)$	$s(i)$
$\alpha=0,\beta=2$	231131	00100 00010 01000 01000 00010 01000
$\alpha=1,\beta=4$	033042	10000 00010 00010 10000 00001 00100
$\alpha=2,\beta=3$	224343	00100 00100 00001 00010 00001 00010
$\alpha=2,\beta=4$	330403	00010 00010 10000 00001 10000 00010
$\alpha=3,\beta=3$	243424	00100 00001 00010 00001 00100 00001
$\alpha=4,\beta=0$	101440	01000 10000 01000 00001 00001 10000

The construction of partitioned MQC code can be divided into two stages. In the first stage, a block of code sequences B_p is constructed, which will be used to construct PMQCC families in the second stage.

Step1: construction of $block\ codes\ (B_p)$.

We first construct a sequence of integer numbers $y_{d,\alpha,\beta}(t)$ for a given prime number p over a finite field $GF(p)$, where $p > 2$. The formula can be expressed as follow:

$$y_{d,\alpha,\beta}(t) = [d(t+\alpha)^2 + \beta](mod\ p) \quad (1)$$

Where $t = 0,1,2,\ldots,p-1$, $d \in \{1,2,\ldots,p-1\}$ and $\alpha,\beta \in \{0,1,2,\ldots,p-1\}$. Table-III shows $y_{a,\alpha,\beta}(t)$ values for $p = 3$ and $d = 1$.

TABLE III
BLOCK CODE EXAMPLE FOR P=3 AND D=1 (B_3)

α, β	B_3	$y(t)$		
		$y(0)$	$y(1)$	$y(2)$
$\alpha = 0, \beta = 0$	$B_{3,0}$	0	1	1
$\alpha = 0, \beta = 1$		1	2	2
$\alpha = 0, \beta = 2$		2	0	0
$\alpha = 1, \beta = 0$	$B_{3,1}$	1	1	0
$\alpha = 1, \beta = 1$		2	2	1
$\alpha = 1, \beta = 2$		0	0	2
$\alpha = 2, \beta = 0$	$B_{3,2}$	1	0	1
$\alpha = 2, \beta = 1$		2	1	2
$\alpha = 2, \beta = 2$		0	2	0

From the above example, we can easily see that, for a given value of t in each group where α is fixed we obtain different values for y(t). We define the group which has the same α as $B_{p,\alpha}$, (i.e. in this example there are three groups ($B_{3,0}$, $B_{3,1}$ & $B_{3,2}$). In Step-2 that the mapping method is introduced we show that $B_{p,\alpha}$ code sequences are orthogonal to each other (i.e. their in-phase CC is 0). However, the in-phase CC for any code pair from different groups is 1.

Step2: construction of the binary code sequences B_p

Next, we introduce the mapping method, which is used to translate the integer sequences $y_{d,\alpha,\beta}(t)$ into the binary code sequences, $S_{d,\alpha,\beta}(i)$. This process can be done by using following expression:

$$S_{d,\alpha,\beta}(i) = \begin{cases} 1, & if\ i = tp + y_{d,\alpha,\beta}(t) \\ 0, & else \end{cases} \tag{2}$$

Where $i = 0,1,2,\ldots,p^2-1$ and $t = \lfloor i/p \rfloor$. The symbol $\lfloor i/p \rfloor$ denotes the largest integer value less than or equal to (i/p). By applying mapping method to B_p, we can get following binary code sequences. Table-IV shows an example of this binary code sequences for prime number p=3 and d=1.

TABLE IV
EXAMPLE OF BINARY BLOCK CODE FOR PRIME NUMBER P=3 AND D=1

α, β	B_3	$y(t)$			$S_{1,\alpha,\beta}(i)$		
		$y(0)$	$y(1)$	$y(2)$	$y(0)$	$y(1)$	$y(2)$
$\alpha = 0, \beta = 0$	$B_{3,0}$	0	1	1	100	010	010
$\alpha = 0, \beta = 1$		1	2	2	010	001	001
$\alpha = 0, \beta = 2$		2	0	0	001	100	100
$\alpha = 1, \beta = 0$	$B_{3,1}$	1	1	0	010	010	100
$\alpha = 1, \beta = 1$		2	2	1	001	001	010
$\alpha = 1, \beta = 2$		0	0	2	100	100	001
$\alpha = 2, \beta = 0$	$B_{3,2}$	1	0	1	010	100	010
$\alpha = 2, \beta = 1$		2	1	2	001	010	001
$\alpha = 2, \beta = 2$		0	2	0	100	001	100

Step3: construction of $partitioned\ codes\ (B'_{p_2})$ and mapping method

Chose a prime number $p_2 \le p$ and repeat Step1 to obtain B'_{p_2} which has the same code construction as B_p. This will be used to construct integer partitioned MQC code sequences $P'_{d_2,\alpha_2,\beta_2}$. Also, the mapping method of $partitioned\ code$ is expressed below:

$$P'_{d_2,\alpha_2,\beta_2}(j) = \begin{cases} B_{p,\alpha}, & if\ j = tp_2 + y_{2_{d_2,\alpha_2,\beta_2}}(t) \\ [null], & else \end{cases} \tag{3}$$

Where $d_2 \in \{1,2,3,..,p_2-1\}$, $\alpha_2,\ \beta_2 \in \{0,1,2,\ldots,p_2-1\}$, $j = 0,1,2,\ldots,p_2^2-1$),$t = \lfloor j/p_2 \rfloor$and $y_{2_{d,\alpha,\beta}}(t)$ represents the sequence which is constructed by using the prime number p_2. The null in the above formula represents '0' binary (not integer 0) and this null matrix has the same dimension as $B_{p,\alpha}$, which is p x p. Let us define matrix $[n] \equiv [null]$, the integer 'n' represents "null" and it will be clear in the following examples when $p = p_2 = 3$, 'n' maps into '000' whereas '0' maps into '100'. The matrix [n] represents the matrix with all elements are filled with 'n'. Hence the new matrix $[n][n]B_{p,\alpha}$ has a dimension of $[p_2 p^2 \times p]$ and the total code length for each user is $(p_2^2 \times p^2)$. Here is an example of integer partitioned MQC code sequences $P'_{d_2,\alpha_2,\beta_2}$ for $d_2 = 1$ and $p = p_2 = 3$ (See Table-V).

TABLE V
EXAMPLE OF BINARY PARTITIONED CODE FOR PRIME NUMBER P=P2=3 AND $d = d_2 = 1$

α_2, β_2	$y_2(t)$			$P'_{d_2,\alpha_2,\beta_2}$		
	$y_2(0)$	$y_2(1)$	$y_2(2)$	$y_2(0)$	$y_2(1)$	$y_2(2)$
$\alpha_2 = 0, \beta_2 = 0$	0	1	1	$B_{3,0}[n][n]$	$[n]B_{3,0}[n]$	$[n]B_{3,0}[n]$
$\alpha_2 = 0, \beta_2 = 1$	1	2	2	$[n]B_{3,0}[n]$	$[n][n]B_{3,0}$	$[n][n]B_{3,0}$
$\alpha_2 = 0, \beta_2 = 2$	2	0	0	$[n][n]B_{3,0}$	$B_{3,0}[n][n]$	$B_{3,0}[n][n]$
$\alpha_2 = 1, \beta_2 = 0$	1	1	0	$[n]B_{3,1}[n]$	$[n]B_{3,1}[n]$	$B_{3,1}[n][n]$
$\alpha_2 = 1, \beta_2 = 1$	2	2	1	$[n][n]B_{3,1}$	$[n][n]B_{3,1}$	$[n]B_{3,1}[n]$
$\alpha_2 = 1, \beta_2 = 2$	0	0	2	$B_{3,1}[n][n]$	$B_{3,1}[n][n]$	$[n][n]B_{3,1}$
$\alpha_2 = 2, \beta_2 = 0$	1	0	1	$[n]B_{3,2}[n]$	$B_{3,2}[n][n]$	$[n]B_{3,2}[n]$
$\alpha_2 = 2, \beta_2 = 1$	2	1	2	$[n][n]B_{3,2}$	$[n]B_{3,2}[n]$	$[n][n]B_{3,2}$
$\alpha_2 = 2, \beta_2 = 2$	0	2	0	$B_{3,2}[n][n]$	$[n][n]B_{3,2}$	$B_{3,2}[n][n]$

Following Step-2 we can obtain the binary code sequences of $B_{p,\alpha}$ and substitute it in Table-V to construct the final partitioned MQC code which is shown in the following Table-VI.

TABLE VI
EXAMPLE OF INTEGER CODE SEQUENCES OF PARTITIONED MQC CODE

User(K)	$y_2(0)$									$y_2(1)$									$y_2(2)$								
1	**0**	**1**	**1**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**0**	**1**	**1**	**n**	**n**	**n**	**n**	**n**	**n**	**0**	**1**	**1**	**n**	**n**	**n**
2	1	2	2	n	n	n	n	n	n	n	n	n	1	2	2	n	n	n	n	n	n	1	2	2	n	n	n
3	2	0	0	n	n	n	n	n	n	n	n	n	2	0	0	n	n	n	n	n	n	2	0	0	n	n	n
4	n	n	n	0	1	1	n	n	n	n	n	n	n	n	n	0	1	1	n	n	n	n	n	n	0	1	1
5	n	n	n	1	2	2	n	n	n	n	n	n	n	n	n	1	2	2	n	n	n	n	n	n	1	2	2
6	n	n	n	2	0	0	n	n	n	n	n	n	n	n	n	2	0	0	n	n	n	n	n	n	2	0	0
7	n	n	n	n	n	n	0	1	1	0	1	1	n	n	n	n	n	n	0	1	1	n	n	n	n	n	n
8	n	n	n	n	n	n	1	2	2	1	2	2	n	n	n	n	n	n	1	2	2	n	n	n	n	n	n
9	n	n	n	n	n	n	2	0	0	2	0	0	n	n	n	n	n	n	2	0	0	n	n	n	n	n	n
....	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
25	**1**	**0**	**1**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**1**	**0**	**1**	**1**	**0**	**1**	**n**	**n**	**n**	**n**	**n**	**n**
26	2	1	2	n	n	n	n	n	n	n	n	n	n	n	n	2	1	2	2	1	2	n	n	n	n	n	n
27	0	2	0	n	n	n	n	n	n	n	n	n	n	n	n	0	2	0	0	2	0	n	n	n	n	n	n

Once parameters $\alpha, \alpha_2, \beta\ and\ \beta_2$ are known, the kth user's code can be obtained by using Eqs. (1) to (3). In short, given prime numbers p and p2 then based on the properties of the code explained earlier we can obtain parameters $\alpha, \alpha_2, \beta\ and\ \beta_2$ as:

$$\alpha = \alpha_2 = \lceil k/p_2 p \rceil - 1 \quad (3a)$$
$$\beta_2 = \lceil k/p \rceil - 1 \quad (3b)$$
$$\beta = MOD\left(\frac{k}{p}\right) - 1 \quad (3c)$$

Where the term $\lceil k/p_2 p \rceil$ represents the smallest integer larger or equal to $(k/p_2 p)$ and MOD is a function where we can get the remainder of (k/p). For example for k=7, p=3 and p2=3 from the above formulae we get $\alpha = \alpha_2 = 0$, $\beta_2 = 2$ and $\beta = 0$.

In Table-VI each integer number (i.e. 0 or 1 or 2 or n) represents a 3 bits' binary code sequence and since in this example, $p_2 = 3$ and $p = 3$ hence, the total length of each user is $p_2^2 \times p^2 = 81$ and the code weight is 9. Since the in-phase CC between any two codes in a group (i.e. for a given$B_{p,\alpha}$) is 0 we can determine the average in-phase CC. The total combinations between any two codes is $\binom{p_2^2 p}{2}$ and the total collisions between any two code sequences is $\left(\binom{p_2^2 p}{2} - \right.$ *p2p2p2p2*. Hence, the average in-phase CC $\bar{\lambda} = \left(1 - p_2 \binom{p_2 p}{2} / \binom{p_2^2 p}{2}\right)$. Finally, the partitioned code can be denoted as $\left(p_2^2 p^2, p_2 p, \left(1 - p_2 \binom{p_2 p}{2} / \binom{p_2^2 p}{2}\right)\right)$.

III. Code Evaluation And Comparison

Comparison between Hadamard, Prime codes, ZCC, MDW, RD, MQC, PDC and PMQCC in terms of code length and code weight for supporting same number of users is shown in Table-VII. Apart from code length and code weight, in phase cross correlation is also an important factor which severely affects the system performance. Details will be discussed in later sections.

TABLE VII
Comparison Between Hadamard, Prime codes, ZCC, MDW, RD, MQC, PD Code and PMQC Code for the same number of users

Code	Code length	Code weight	No. of users
Hadamard	32	16	25
Prime code	841	29	25
ZCC	100	4	25
MDW	77	4	25
RD	28	3	25
MQC	30	5	25
PD code	50	4	25
PMQC code	81	9	25

A. *Performance analysis of partitioned diagonal code*

Partitioned diagonal code (PDC) can be denoted as $\left(MS(S-1)/2,\ S-1,\ M\binom{S}{2}/\binom{MS}{2}\right)$ and its code properties can be expressed as:

$$\sum_{i=1}^{N} C_k(i) C_l(i) = \begin{cases} S-1, & k = l \\ M\binom{S}{2}/\binom{MS}{2}, & k \neq l \end{cases} \quad (4a)$$

Hence,

$$\sum_{i=1}^{N} C_k(i) \overline{C_l}(i) = \begin{cases} 0, & k = l \\ \left(S - 1 - M\binom{S}{2}/\binom{MS}{2}\right), & k \neq l \end{cases} \quad (4b)$$

Where $C_l(i)$ and $C_k(i)$ represent the binary numbers of the l[th] and k[th] users in the i position, respectively. Where $C_l(i)$, $C_k(i)$ and $\overline{C_l}(i)$ denote the binary numbers of the l[th] and k[th] users in the i position, and complement binary numbers of l[th] user in i position, respectively. In the following analysis for simplicity we assume (i) the light source is un-polarized and its spectrum amplitude is flat, (ii) the amplitude of each power spectral width is constant, (iii) the received power is identical and (iv) the user is synchronized. It should be noted that asynchronous system can also be used however, in this paper we have employed synchronous system to simplify the analysis. The variance of photocurrent can be expressed as [15].

$$\langle I_{noise}^2 \rangle = \langle I_{PIIN}^2 \rangle + \langle I_{shot\ noise}^2 \rangle + \langle I_{thermal}^2 \rangle = I^2 B \tau_c + 2eIB + \frac{4K_b T_n B}{R_L} \quad (5)$$

Where PIIN denotes the phase induced intensity noise, e is the electron charge; I is the average photocurrent; B is the noise-equivalent electrical bandwidth; τ_c is the coherence time of source, which can be calculated as $\int_0^\infty G(f)^2\, df / \left[\int_0^\infty G(f)\, df\right]^2$ [5], $G(f)$ represents the single sideband power spectral density (PSD); T_n is the absolute receiver noise temperature; K_b is the Boltzmann's constant and R_L is the receiver load resistor. Based on the above mentioned assumptions, the received optical signals $r(v)$ can be expressed as [20]:

$$r(f) = \frac{P_{sr}}{\Delta f} \sum_{k=1}^{K} d_k \sum_{i=1}^{N} C_k(i) \left\{ u\left[f - f_0 - \frac{\Delta f}{2N}(-N + 2i - 2)\right] - u\left[f - f_0 - \frac{\Delta f}{2N}(-N + 2i)\right] \right\} \quad (6)$$

Where f is the optical source frequency, K is the number of active users less than or equal to $M \times S$, P_{sr} is the received signal power, d_k is the data bit of the k^{th} the user, u is the unit step function, f_0 is the central optical frequency, Δf is the optical source bandwidth in Hertz and N is the length of code. Therefore, the received signal PSD at the receivers PD-1 and PD-2 (see Fig.1) for the first receiver during one bit period can be expressed as [20]:

$$G_1(f) = \alpha \frac{P_{sr}}{\Delta f} \sum_{k=1}^{K} d_k \sum_{i=1}^{N} C_k(i)\, \overline{C_l}(i) \left\{ u\left[f - f_0 - \frac{\Delta f}{2N}(-N + 2i - 2)\right] - u\left[f - f_0 - \frac{\Delta f}{2N}(-N + 2i)\right] \right\}$$

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(7)

$$G_2(f)=\frac{P_{sr}}{\Delta f}\sum_{k=1}^{K}d_k\sum_{i=1}^{N}C_k(i)\,C_l(i)\left\{u\left[f-f_0-\frac{\Delta f}{2N}(-N+2i-2)\right]-u\left[f-f_0-\frac{\Delta f}{2N}(-N+2i)\right]\right\}$$

(8)

Where $\alpha=1/\left(S-1-M\binom{S}{2}/\binom{MS}{2}\right)$ is the coefficient of the amplifier in the complement path of the balance detection as shown in see Fig.1. The photocurrent can be obtained as:

$$I=I_2-I_1=\Re\int_0^{\infty}G_2(f)\,df-\Re\int_0^{\infty}G_1(f)\,df=\Re\frac{P_{sr}(S-1)}{N}d_l$$

(9)

Where $\Re$ is the responsivity of the photodetector. We have:

$$\int_0^{\infty}G_1(f)\,df=\alpha\frac{P_{sr}}{\Delta f}\sum_{k=1,k\neq l}^{K}\left[\left(S-1-\frac{M\binom{S}{2}}{\binom{MS}{2}}\right)\frac{\Delta f}{N}d_k\right]=\frac{P_{sr}}{N}\sum_{k=1,k\neq l}^{K}d_k$$

(10)

$$\int_0^{\infty}G_2(f)\,df=\frac{P_{sr}}{\Delta f}\left\{wd_l\frac{\Delta f}{N}+\sum_{k=1,k\neq l}^{K}\frac{\Delta f}{N}d_k\right\}=\frac{P_{sr}}{N}(S-1)d_l+\frac{P_{sr}}{N}\sum_{k=1,k\neq l}^{K}d_k$$

(11)

In order to calculate $\int_0^{\infty}G_1^2(v)\,dv$ and $\int_0^{\infty}G_2^2(v)\,dv$, we need to know the spectra density function of the received superimposed signal. An example of PSD of the received signal denoted by $G'(v)$ is given in Fig.2 where $\alpha(i)$ is the amplitude of i_{th} spectral slot with width of $(\Delta V/N)$ [19]. Hence, the integral of $G'^2(v)$ can be expressed as:

$$\int_0^{\infty}G'^2(v)dv=\frac{\Delta v}{N}\sum_{i=1}^{K}a^2(i)$$

(12)

Also, the integral of $G_l^2(v)$ and $G_2^2(v)$ can be calculated as follow:

$$\int_0^{\infty}G_1^2(v)\,dv=\alpha^2\frac{{P_{sr}}^2}{N\Delta v}\sum_{i=1}^{N}\left\{\overline{C_l}(i)\cdot\left[\sum_{k=1}^{K}d_kc_k(i)\right]\cdot\left[\sum_{m=1}^{K}d_mc_m(i)\right]\right\}$$

(13)

$$\int_0^{\infty}G_2^2(v)\,dv=\frac{{P_{sr}}^2}{N\Delta v}\sum_{i=1}^{N}\left\{C_l(i)\cdot\left[\sum_{k=1}^{K}d_kc_k(i)\right]\cdot\left[\sum_{m=1}^{K}d_mc_m(i)\right]\right\}$$

(14)

When all the users are transmitting bit 1 we have:

$$\sum_{k=1}^{K}C_k(i)\approx\frac{Kw}{N}=\frac{K(S-1)}{N}$$

(15)

By substituting the code properties given in Eqs. (4a) and (4b) into Eqs.(13) and (14), respectively, the noise power can be written as:

$$\langle I_{PIIN}^2\rangle=I_1^2B\tau_{c1}+I_2^2B\tau_{c2}=B\Re^2\left[\int_0^{\infty}G_1^2(v)\,dv+\int_0^{\infty}G_2^2(v)\,dv\right]$$
$$=B\Re^2\left\{\alpha^2\frac{{P_{sr}}^2}{N\Delta v}\sum_{i=1}^{N}\left\{\overline{C_l}(i)\cdot\left[\sum_{k=1}^{K}d_kc_k(i)\right]\cdot\left[\sum_{m=1}^{K}d_mc_m(i)\right]\right\}+\frac{{P_{sr}}^2}{N\Delta v}\sum_{i=1}^{N}\left\{C_l(i)\cdot\left[\sum_{k=1}^{K}d_kc_k(i)\right]\cdot\left[\sum_{m=1}^{K}d_mc_m(i)\right]\right\}\right\}$$

(16)

$$\langle I_{PIIN}^2\rangle=B\Re^2\frac{K(S-1)}{N}\left\{\alpha^2\frac{{P_{sr}}^2}{N\Delta v}\left[(K-1)(S-1-\frac{M\binom{S}{2}}{\binom{MS}{2}})\right]+\frac{{P_{sr}}^2}{N\Delta v}[K+S-2]\right\}$$

(17)

As for shot noise, it can be expressed as:

$$\langle I_{shot\ noise}^2\rangle=2eB(I_1+I_2)=2eB\Re\left[\int_0^{\infty}G_1(v)\,dv+\int_0^{\infty}G_2(v)\,dv\right]$$
$$=2eB\Re\left[\frac{P_{sr}}{N}\sum_{k=1,k\neq l}^{K}d_k+\frac{P_{sr}}{N}(S-1)d_l+\frac{P_{sr}}{N}\sum_{k=1,k\neq l}^{K}d_k\right]=2eB\Re P_{sr}\left(\frac{2K-3+S}{N}\right)$$

(18)

Finally, the thermal noise can be calculated as:

$$\langle I_{thermal}^2\rangle=\frac{4K_bT_nB}{R_L}$$

(19)

The probability of each user sending bit 1 is 50%, thus, the above equations need to be multiply by 0.5 that is:

$$\langle I_{noise}^2\rangle=B\Re^2\frac{Kw{P_{sr}}^2}{2N^2\Delta v}\left\{\alpha^2\left[(K-1)\left(S-1-\frac{M\binom{S}{2}}{\binom{MS}{2}}\right)\right]+[(K-2)+S]\right\}+eB\Re P_{sr}\left(\frac{2K-3+S}{N}\right)+\frac{4K_bT_nB}{R_L}$$

(20)

and

$$I^2=(I_2-I_1)^2=\left(\Re\frac{P_{sr}w}{N}\right)^2=\left(\Re\frac{P_{sr}(S-1)}{N}\right)^2$$

(21)

Finally, the average signal to noise ratio (SNR) due to PIIN, shot noise and thermal noise has been derived as below:

$$SNR=\frac{(I_2-I_1)^2}{\langle I_{noise}^2\rangle}=\frac{\left(\Re\frac{P_{sr}(S-1)}{N}\right)^2}{\langle I_{PIIN}^2\rangle+\langle I_{shot\ noise}^2\rangle+\langle I_{thermal}^2\rangle}$$

(22)

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Then, bit error rate can be calculated as:

$$P_e = \frac{1}{2} erfc\left(\sqrt{\frac{SNR}{8}}\right) \tag{23}$$

Where $erfc(x) = \frac{1}{\sqrt{\pi}}\int_x^{\infty} e^{-t^2}dt$. In an optical CDMA system, the pulse overlapping often occurs especially when active user number is large. Thus according to the central limit theorem it is reasonable to use Gaussian approximation here.

B. Performance analysis of partitioned modified quadratic congruence code

As for partitioned modified quadratic congruence code (PMQCC) family, the code can be denoted as $\left(p_2^2p^2, p_2p, 1-\right.$ *p2p2p2p22p2* and the code properties are given below:

$$\sum_{i=1}^{N} C_k(i)C_l(i) = \begin{cases} p_2p, & k = l \\ 1 - p_2\binom{p_2p}{2} / \binom{p_2^2p}{2}, & k \neq l \end{cases} \tag{24a}$$

Hence:

$$\sum_{i=1}^{N} C_k(i)\overline{C_l}(i) = \begin{cases} 0, & k = l \\ \left(p_2p - \left(1 - p_2\binom{p_2p}{2} / \binom{p_2^2p}{2}\right)\right), & k \neq l \end{cases} \tag{24b}$$

Similarly, the PSD and photo current can be expressed as:

$$\int_0^{\infty} G_1(v)\,dv = \alpha\frac{P_{sr}}{\Delta v}\sum_{k=1,k\neq l}^{K}\left(p_2p - \left(1 - p_2\binom{p_2p}{2} / \binom{p_2^2p}{2}\right)\right)\frac{\Delta v}{N}d_k = \frac{P_{sr}}{N}\sum_{k=1,k\neq l}^{K} d_k \tag{25}$$

$$\int_0^{\infty} G_2(v)\,dv = \frac{P_{sr}}{\Delta v}\left\{wd_l\frac{\Delta v}{N} + \sum_{k=1,k\neq l}^{K}\frac{\Delta v}{N}d_k\right\} = \frac{P_{sr}}{N}p_2pd_l + \frac{P_{sr}}{N}\sum_{k=1,k\neq l}^{K} d_k$$

$$I = I_2 - I_1 = \Re\int_0^{\infty} G_2(v)\,dv - \Re\int_0^{\infty} G_1(v)\,dv = \Re\frac{P_{sr}p_2p}{N}d_l \tag{26}$$

Where K is the number of active users less than or equal to p^2p_2 and the other parameters remain the same as shown in Equation-6.

Next, the integral of $G_l^2(v)$ and $G_2^2(v)$ are given below:

$$\int_0^{\infty} G_1^2(v)\,dv = \alpha^2\frac{{P_{sr}}^2}{N\Delta v}\sum_{i=1}^{N}\left\{\overline{C_l}(i)\cdot\left[\sum_{k=1}^{K} d_k c_k(i)\right]\cdot\left[\sum_{m=1}^{K} d_m c_m(i)\right]\right\} \tag{27}$$

$$\int_0^{\infty} G_2^2(v)\,dv = \frac{{P_{sr}}^2}{N\Delta v}\sum_{i=1}^{N}\left\{C_l(i)\cdot\left[\sum_{k=1}^{K} d_k c_k(i)\right]\cdot\left[\sum_{m=1}^{K} d_m c_m(i)\right]\right\} \tag{28}$$

And

$$\sum_{k=1}^{K} C_k(i) \approx \frac{Kw}{N} = \frac{Kp_2p}{N} \tag{29}$$

Substituting equation (24a) and equation (24b) into the equation (28) and equation (27), respectively. We can get:

$$\langle I_{PIIN}^2\rangle = I_1^2B\tau_{c1} + I_2^2B\tau_{c2} = B\Re^2\left[\int_0^{\infty} G_1^2(v)\,dv + \int_0^{\infty} G_2^2(v)\,dv\right]$$
$$= B\Re^2\frac{Kw}{N}\left\{\alpha^2\frac{{P_{sr}}^2}{N\Delta v}[(K-1)(w-ipcc)] + \frac{{P_{sr}}^2}{N\Delta v}[(K-1)+w]\right\}$$
$$= B\Re^2\frac{K{P_{sr}}^2}{\Delta v(pp_2)^3}\left(\frac{(K-1)}{\left(p_2p - \left(1 - p_2\binom{p_2p}{2} / \binom{p_2^2p}{2}\right)\right)} + K + p_2p - 1\right) \tag{30}$$

Also, the shot noise, signal current density, signal-to-noise ratio (SNR) and BER can be obtained from the following expressions:

$$\langle I_{shot\ noise}^2\rangle = 2eB(I_1 + I_2) = 2eB\Re\left[\int_0^{\infty} G_1(v)\,dv + \int_0^{\infty} G_2(v)\,dv\right]$$
$$= 2eB\Re\left[\frac{P_{sr}}{N}\sum_{k=1,k\neq l}^{K} d_k + \frac{P_{sr}}{N}p_2pd_l + \frac{P_{sr}}{N}\sum_{k=1,k\neq l}^{K} d_k\right]$$
$$= 2eB\Re P_{sr}\left(\frac{2K + p_2p - 2}{N}\right) \tag{31}$$

$$I^2 = (I_2 - I_1)^2 = \left(\Re\frac{P_{sr}w}{N}\right)^2 = \left(\Re\frac{P_{sr}p_2p}{N}\right)^2 \tag{32}$$

$$SNR = \frac{(I_2 - I_1)^2}{\langle I_{noise}^2\rangle} = \frac{\left(\Re\frac{P_{sr}p_2p}{N}\right)^2}{\langle I_{PIIN}^2\rangle + \langle I_{shot\ noise}^2\rangle + \langle I_{thermal}^2\rangle} \tag{33}$$

$$P_e = \frac{1}{2} erfc\left(\sqrt{\frac{SNR}{8}}\right) \tag{34}$$

IV. Performance Analysis of PDC And PMQC

We have employed the SAC-OCDMA system based on balance detection and explored performances of both PDC and PMQCC as compared with MQC code using the parameter listed in Table-VIII. In our simulations we have assumed that the received signal power is $P_{sr} = -10dBm$.

TABLE VIII
TYPICAL PARAMETERS USED IN THE CALCULATION

Symbol	Quantity	Value
η	PD Quantum Efficiency	0.6
Δv	Thermal Source Linewidth	$3.75THz$
λ_0	Operating Wavelength	$1.55\mu m$
B_b	Data Bit Rate	$155Mbps$
T_r	Receiver Noise Temperature	$300K$
R_L	Receiver Load Resistor	1030Ω
P_r	Power at receiver	-10dBm

Figure 3 shows the simulation results of both PDC and MQC codes. The noise floor (i.e. BER= 10^{-9}) is also shown. The results clearly show that MQC cannot support more than 160 active users, because its BER becomes more than the noise floor level whereas, the new PDC can support well above 160 active users with BER much lower than the noise floor level. It should be noted that the code lengths of these two codes are almost the same.

Since SAC employs spectral and amplitude to encode/ decode the data bit thus this system is suitable for both synchronous and asynchronous transmissions. Detail performance of asynchronous system can be found in [21]. In this paper, we have focused on synchronous system and only need to consider the value of auto/cross-correlation at each synchronized time.

Figure 4 shows the simulation results of the transmitting data stream (10101) by two different users s_1 and s_2 when employing PDC. Both s1 and s2 are shown in bold in Table-I. From Fig.4, the maximum auto and cross correlations are, respectively, 6 and 3. Also, at each synchronized time T, the peak value of the auto correlation is exactly equal to the code weight (7-1=6) and the peak value of cross correlation is equal to 1 because M=1 and $\lambda = M \times \binom{S}{2} / \binom{MS}{2} = 1$.

The performance analysis of PMQCC as compared with MQC code is shown in the Fig5. The results clearly show that MQC code can only support 110 active users whereas PMQCC can support more than 125 active users. Hence, by applying partition and iteration method we can improve the MQC performance.

Similarly, the auto and cross correlations of PMQCC are shown in the Fig.6 where s_1 and s_{25} are the 1^{st} and 25^{th} users' codes (see Table-6) used to encode the data stream (10101). The results show that the maximum values of AC and CC are 9 and 3, respectively. Moreover, AC reaches its peak value at each synchronized time T whereas CC value remains 1. Consequently, in a synchronous system PDC performance is much better (i.e. has a very low BER).

V. Conclusion

Two new codes hereby referred to as 'PDC' and 'PMQCC' are introduced for the SAC-OCDMA system. Their properties are explored and compared with MQC code family. The performance analysis shows that both codes can improve the SAC-OCDMA system performance (both offer higher number of simultaneous active user). Because, the length of PDC is larger than that of MQC code. We have introduced partition method to reduce the code length and also increase the total number of simultaneous users. As for the PMQCC, partition method is also employed to increase the total number of simultaneous users.

The simulation results show that each of the two proposed new codes has better BER performance as compared with MQC and hence accommodate 11% (PDC) and 13% (PMQCC) more simultaneous users.

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